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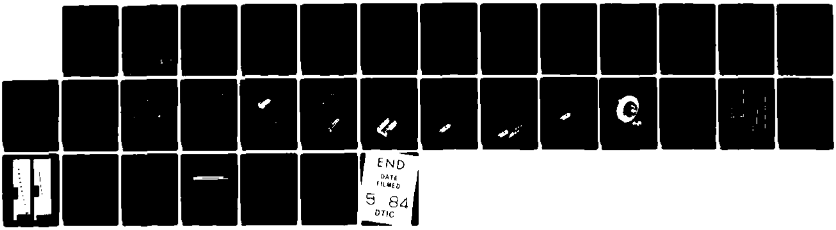

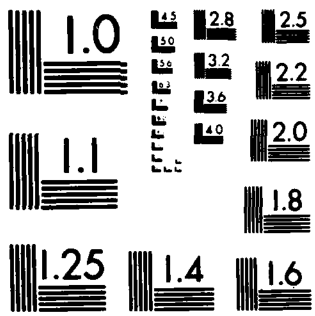

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REPORT

MRL-R-894

EXPERIMENTAL ELECTROMAGNETIC LAUNCHERS AT MRL

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The design and construction of small calibre rail-type *electromagnetic* launchers are described. Bore sizes of 6 x 8 mm or 10 x 10 mm cross section are used and barrel lengths vary from 200 mm to 2 m. Sufficient information is provided to reproduce any of the devices, all of which are proving to be very useful experimentally. Examples of results are presented.

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EXPERIMENTAL ELECTROMAGNETIC LAUNCHERS AT MRL

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ABSTRACT

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CONTENTS

EXPERIMENTAL ELECTROMAGNETIC LAUNCHERS

AT MRL

1. INTRODUCTION

A theoretical and experimental program on electromagnetic launchers (EML) has been pursued at Materials Research Laboratories since 1979. The work has concentrated on the railgun type EML which utilises a plasma armature to accelerate a projectile.

A one-dimensional simulation code was developed by Thio [1,2] which has shown good correlation with experimental results [3]. In the evolution of the current research program several successful railgun devices have been designed and constructed. This report documents the designs and design parameters in sufficient detail for others to construct similar experimental devices, and it may serve as a guide for development of new devices.

The simplest version of a rail-type accelerator consists of a pair of conducting rails connected to a power source. A wire or foil fuse between the rails explodes (rapid vapourisation) with the onset of current producing a plasma armature. The current in the rails produces a strong magnetic field which acts on the current in the plasma producing a force which accelerates this plasma and projectile (Fig. 1). All the rail-launcher devices built for the current program are small calibre, up to 10 mm square bore, and have been designed to be powered by capacitor banks of up to 500 kJ energy capacity. The largest launcher being constructed has a maximum design current of 500 kA.

It has been fairly common in EML programs to describe the performance of a launcher in terms of the velocity achieved for a given projectile mass. On this basis, the launchers described herein are for accelerating small plastic projectiles of masses between 0.3 and 1 g in the velocity range 0.2 to 10 km/s.

2. ELECTRICAL CIRCUITS

The same basic circuit design is used for all our experimental railguns. The power is provided by capacitor banks; the stored energy is varied by varying the number of capacitors connected in parallel and varying the voltage impressed upon them between 2 and 10 kV. The different capacitor banks used are represented by the following list:

(i) Two 60 μF capacitors.

(ii) Eight Maxwell 200 μF capacitors (1600 μF).

(iii) 34 BICC capacitors with total capacitance of 2652 μF.

(iv) Up to 50 Maxwell 200 μF capacitors (10000 μF).

(v) (iii) and (iv) connected in parallel to give 12650 μF.

Inductors are used in the power circuit to provide current pulses of favourable shapes. Either copper coils or an aluminium loop are used; the nominal dimensions of which are shown in Figure 2. The copper coil has an inductance of 2.8 μH. For some experiments two coils have been connected in series to give an inductance of 5.6 μH. In the larger ERGS devices (ERGS is acronym for Experimental Rail-Gun System) a loop of aluminium forms the inductor (Fig. 2). This has an inductance of 6.3 μH. Switching has been accomplished to date using simple spark gap devices for both the main switch and the crowbar switch. The main switch is initiated either electrically or mechanically. In the electrical method a high voltage spark is induced from a trigger electrode to one of the main switch electrodes. The spark initiates electrical breakdown between the electrodes and current avalanches across the gap. Using mechanical means, a piece of aluminium foil mounted on the end of a plastic rod is thrust into the gap between the electrodes (Fig. 3) on receipt of the firing signal. The foil is vaporised thus closing the main switch and allowing the current to avalanche across it.

The crowbar switch is a little more difficult to initiate because instead of firing with the maximum voltage standing between the gap, the crowbar needs to be fired at or near zero standoff voltage. This is accomplished by the circuit represented in Figure 4. Once the voltage reverses on the capacitor bank current flows through the fuse wire causing explosive vapourisation. This initiates breakdown across the spark gap switch which takes the capacitor bank out of the main circuit - the railgun is then effectively driven by an LR circuit. More detail appears in a short paper on the crowbar switch design [4].

All electrical bus-bars are either copper or aluminium and connections are made so that resistance is kept low.

Residual inductor energy remaining after projectile exit from the railguns is usually dissipated by electrodes fastened to the muzzle ends of the rails. One design is shown in Figure 5 in which the gap between the

dissipating electrodes is smaller than that between the rails so that as the plasma leaves the gun it expands into these dissipating electrodes and thus minimises further damage to the muzzle end of the rails.

3. RAILGUN DESIGNS

3.1 Rapid

The acronym means Railgun Armature (Plasma) Investigation Device. This design provides a small accelerator which has the potential to achieve projectile velocities up to 3 km/s with a 6 x 8 x 6 mm or 6 x 8 x 8 mm polycarbonate or vulcanised cellulose fibre projectile. In addition the design facilitates optical photography of events in the bore of the railgun by using a transparent supporting medium. Provision is also made for inserting probes into the edge of the bore of the device.

Figure 6 is a schematic drawing showing the basic configuration and dimensions of RAPID. The rails in this device are of 10 mm square high conductivity copper. The corners of the rails are radiused, as are those in the rail grooves in the polycarbonate supporting sections, so that the tendency for corner cracking of the support is reduced. A particular reason for selecting square section rails was that they could be rotated after one or more firings to give a clean face and thus reduce the material wastage and rail manufacturing needs. Photographs of RAPID are shown in Figure 7.

A smaller version of RAPID, called mini-RAPID, has been used to study rail damage due to firing (Fig. 8). This device was designed so that rails could be quickly replaced. The rail material in this system is 0.6% Cd-Cu which is the material used in larger railguns described later.

The 0.6% Cd-Cu alloy was chosen because of its availability, its rapid work hardening characteristics and its resistance to annealing, and its high conductivity (about 90% of that of pure copper).

3.2 ERGS Type Accelerators

The acronym ERGS comes from Experimental Rail-Gun System. There are several devices under this designation. They have been designed to carry the main experimental burden of our program to investigate the electrical and physical phenomena occurring during the firing of electromagnetic railguns. Energies from 50 to 500 kJ can be dumped into ERGS devices.

3.2.1 ERGS-IA

This is a 200 mm long railgun with the structural arrangement as shown in Figure 9. The Cu-0.6% Cd rails are backed by alumina ceramic and two more pieces of ceramic set the rails apart to form the bore of the railgun. This assembly is potted in epoxy resin reinforced with silica

powder and finally wound with Kevlar fibre in epoxy. Rail removal from this 200 mm barrel was accomplished by cooling the rails with liquid nitrogen and then pulling the rails from the muzzle end. New rails were inserted as the old ones were removed. However, due to cracking of the ceramic this cannot be repeated more than about 2 or 3 times.

3.2.2 ERGS-IB

This is an 800 mm long railgun of the same design as ERGS-IA. Rail removal was accomplished after the first firing of this device [3]. However great difficulty was encountered in re-inserting a second set of rails, which means that this sort of construction has very limited use for experimental railguns.

3.2.3 ERGS-IM

To produce a railgun which could be dismantled and used repeatedly we chose the design shown in Figure 10. The rails are separated by a length of vulcanised cellulose fibre material which resists both the arc damage and the induced loads during firing. This material is easily machined and so is much more convenient than the ceramic spacers used in the ERGS-IA and B devices. The M in ERGS-IM signifies the use of Micarta, a high-density, high-strength glass fibre epoxy composite (G-11 qualified under MIL-P-18177), as the main structural supporting material in the barrel. Our first device of this kind was fired on about 20 occasions with capacitor bank energies ranging up to 250 kJ. The mode of failure was delamination of the glass fibre epoxy along what appeared to be a layer where insufficient penetration (or wetting) by the epoxy was apparent; we assumed this to be a manufacturing fault.

3.2.4 ERGS-2

Devices under the acronym ERGS-2 have been designed and are being constructed. The design is based on a square bore 10 mm x 10 mm with alumina ceramic separating and backing the rails. Finite element analysis of the stresses involved led us to choose the ceramic configuration as shown in Figures 11a,b. The bursting stresses are contained by a Kevlar epoxy wound outer barrel.

This device is designed to take energy inputs up to 500 kJ and currents up to 500 kA. A short version, ERGS-2A, is 200 mm long and will be used for preliminary test firings.

4. EXTENSION OF THE ERGS PROGRAM

A segmented launcher has been designed with the specifications shown in Figure 12. The design calls for connection of the first segment to a 200 kJ capacitor bank and the second segment to a 300 kJ capacitor bank.

5. PROJECTILE DESIGN

Simple projectiles are used in the current railguns, being made from either polycarbonate or vulcanised cellulose fibre composite. For the 6 x 8 mm bore railguns (RAPID, ERGS-I) a cuboid 6 x 8 x 6 mm is used (Fig. 13). The back face is chamfered and the plasma producing foil is glued to it. The chamfer allows good contact between foil and rails particularly when the projectile-foil is muzzle-loaded.

For some experiments we require a lighter projectile and a grooved design (Fig. 13) is used. This provides stability in the barrel section while giving a weight reduction of up to 44%.

6. INSTRUMENTATION

Our experiments have been designed to test theoretical calculations and to assist in understanding the physical phenomena involved in plasma driven railguns. We have therefore concentrated effort on instrumentation and Figure 14 schematically shows the data acquisition system used. A brief description follows but more extensive and detailed information is to be provided in a separate report [5].

High speed transient recorders are used to capture current and voltage information. To measure current, Rogowski belts are used and the outputs from these are fed into the recorders. Voltages are recorded at various points by using high voltage probes interfaced with the transient recorders. Capacitor voltage, breech voltage and muzzle voltage are measured in this way. Triggering of the recorders is critical and it can either be done with a time delay associated with initiation of the main switch, or by using a Rogowski belt on the inductor which signals the start of current flow in the railgun. We have found the latter method more reliable and controllable in conjunction with pretrigger facilities of the recorders.

Acceleration in the bore and velocity of flight are important records in any firing. Small pickup coils placed near the bore are used to give a signal as the current carrying plasma passes, and by reference to a time scale, velocity and acceleration can be calculated. Out-of-bore velocity measurements are done in a number of ways to give cross references. As the projectile leaves the muzzle it passes through a laser screen; it then breaks a fine pencil lead and interrupts a current and finally breaks a wire screen as it enters a ballistic pendulum. These events are all recorded against time and thus a number of velocity readings can be calculated. Simultaneous use of these methods provides a high probability of obtaining several velocity measurements.

All data which are captured and stored on the transient recorders are dumped onto a microcomputer via an IEEE-488 data bus. The digital data thus stored on the computer can be manipulated into various forms (eg for analogue display plots) and programs have been written to calculate a number

of parameters such as power dumped into the rails, energy dissipated in the various sections of the railgun system, and various operating efficiencies (see Ref. [6] for detail on analysis of results).

7. RAILGUN PERFORMANCE

7.1 Rapid

Many firings with devices of this type have been carried out; energy inputs have varied from 7.2 to 29 kJ at voltages from 3 to 6 kV giving currents up to 100 kA. The maximum velocity using this system is about 1 km/s. Typical recordings from a RAPID firing are shown in Figure 15.

The transparent barrel of the RAPID device has facilitated high speed optical photography. Examples of framing and streak camera photographs of the plasma are shown in Figure 16. This is an area which is receiving detailed attention at present in an effort to obtain density profiles from the plasma photographs from which some plasma properties may be inferred. Various kinds and weights of plasma initiating foils are being used.

The polycarbonate supports used for the RAPID launcher have proved remarkably good. Damage to the areas exposed to the bore has been very low; between firings a black deposit is removed and the surface polished. The bodies stand up to the rigors of firing with no apparent cracking even after as many as 50 firings over the full range of energies given above.

7.2 ERGS-I

The results from the first firing of ERGS-I have been published separately [3]. A capacitor bank of 2611 μF was charged to 6.9 kV and was connected to the railgun via a 6.3 μH inductor. The maximum current recorded was 124 kA and a terminal projectile velocity of 1.2 km/s was achieved.

7.3 ERGS-IM

A series of 12 experiments was conducted using an ERGS-IM device. A capacitor bank of 6211 μF was discharged from 3, 4.2, 5, 6 and 7 kV. Duplicate (at least) shots were conducted at each voltage. Results and analyses obtained from these firings are being reported separately [6]. The highest velocity obtained in these firings was 3.3 km/s. An example of the range of results recorded in the ERGS-IM firing is presented in Figure 17.

A detailed examination of the damage to the rails used in the ERGS-IM firings is underway. The linking of damage analysis with the firing results is expected to give quite comprehensive data on rail damage phenomena. This will also be reported separately.

8. COURSE OF EML WORK AT MRL

The research program at MRL has included a balanced theoretical and experimental approach and we are continuing these thrusts. The PARA simulation code [2] has been used to design experiments and to predict results; the analysed results of experiments are compared with these predictions and in most cases to date quite good agreement has been obtained. The various assumptions in PARA are being examined carefully and a more comprehensive and general simulation code is being developed. To obtain a thorough understanding of plasma driven railguns the properties and behaviour of the plasma must be fully elucidated. This is a major thrust of our experimental program now that the several railgun devices and their associated instrumentation have been proved. We are attempting to obtain temperature profiles in the plasma, examine the way a plasma extends during acceleration, and determine its composition against time. Experiments are in hand to measure the magnetic field at several places in the railgun.

The other main thrust is to understand, and then determine ways to eliminate or minimise, damage to the rails and other parts of the railgun. Metallurgical examinations of rails after firing have allowed us to characterise the sorts of damage which occur. Experiments are being conducted to examine different rail materials and different plasma initiating foils. We will also examine effects of surface plating on the rails and of design changes to minimise the massive damage associated with starting a railgun firing with the projectile at rest.

9. ACKNOWLEDGEMENTS

The authors wish to thank Messrs Allen Jenkins, Brian Jones and Mike Astill for their technical assistance in construction and experimental work. The design and drafting contributions of Mr John Thomas are gratefully acknowledged and we thank Mr Ian MacIntyre for provision of high speed photography. We are very pleased to acknowledge the support of DARPA, in particular Dr Harry D. Fair Jr., and the overall guidance and support of Mr Wynford Connick at MRL.

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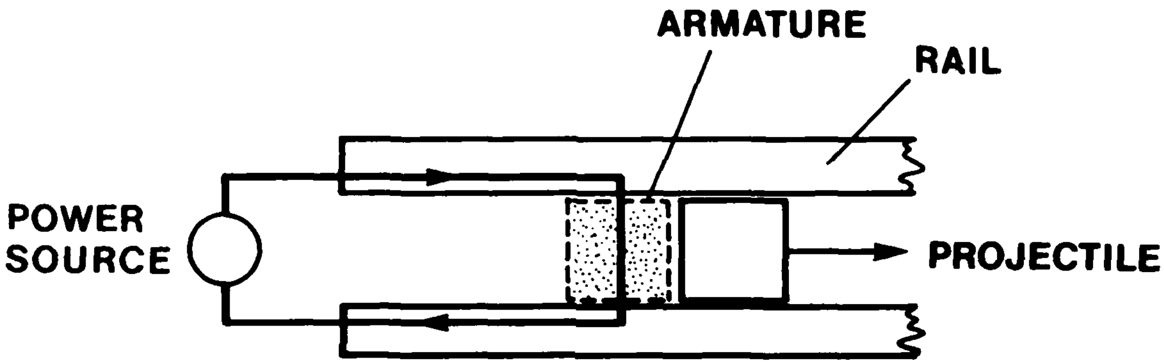
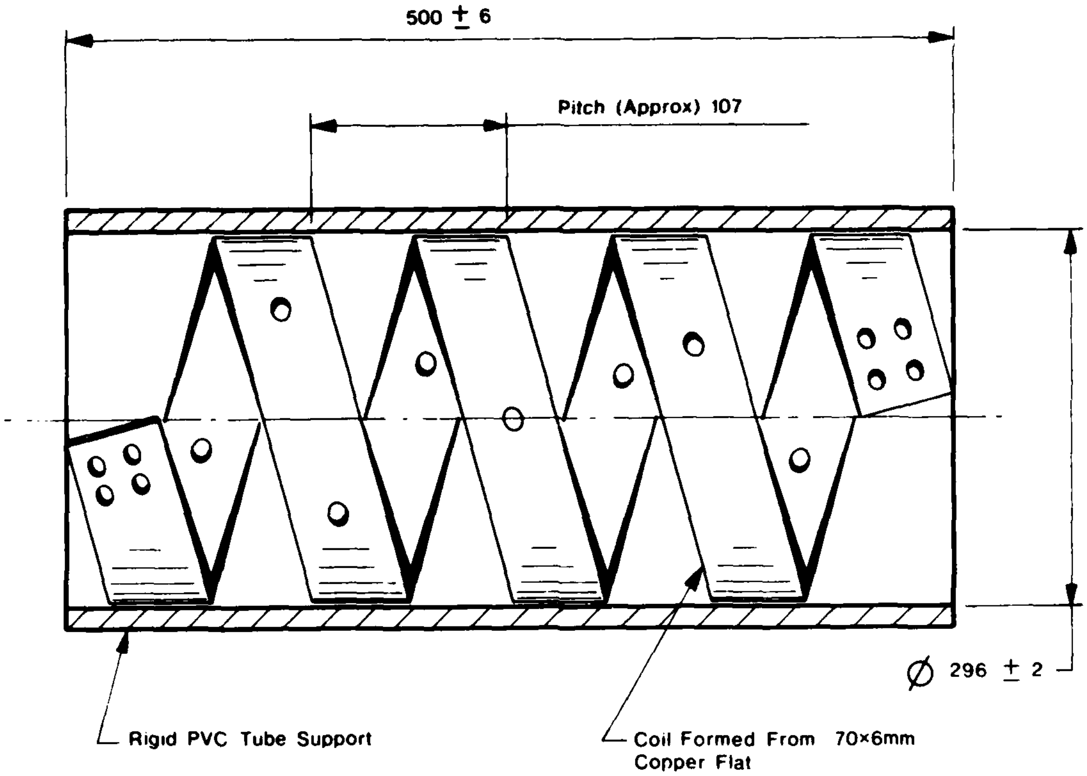
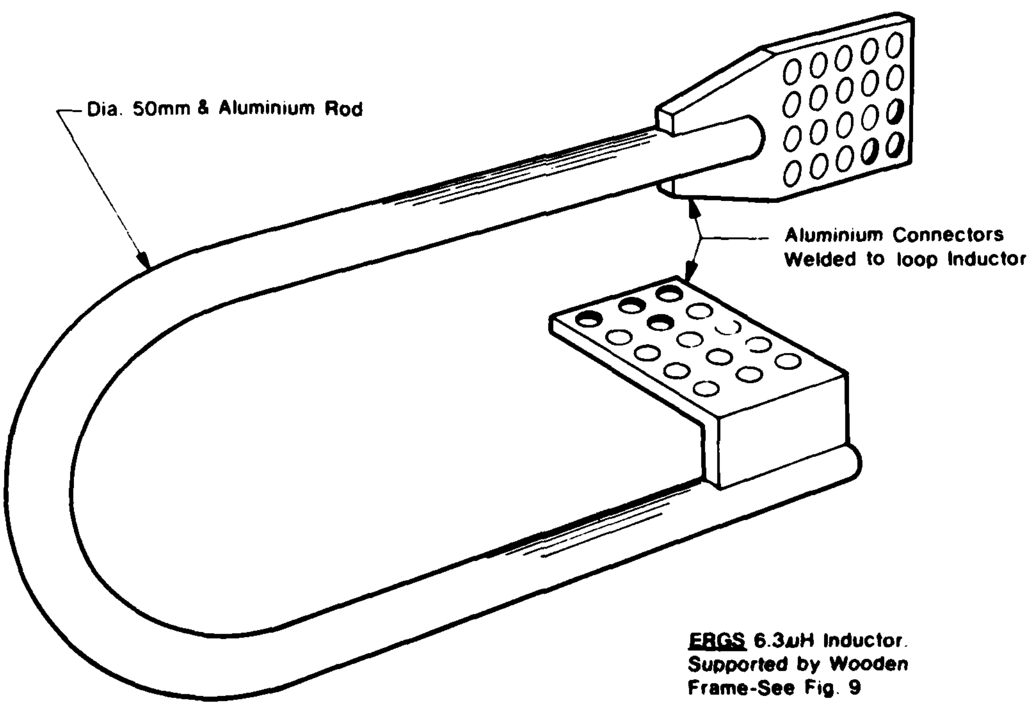


FIGURE 1 Basic configuration of a plasma-armature rail launcher



(dimensions in mm)

COIL INDUCTOR



LARGE INDUCTOR

FIGURE 2 Design of Inductors used in the RAPID and ERGS Rail-Guns

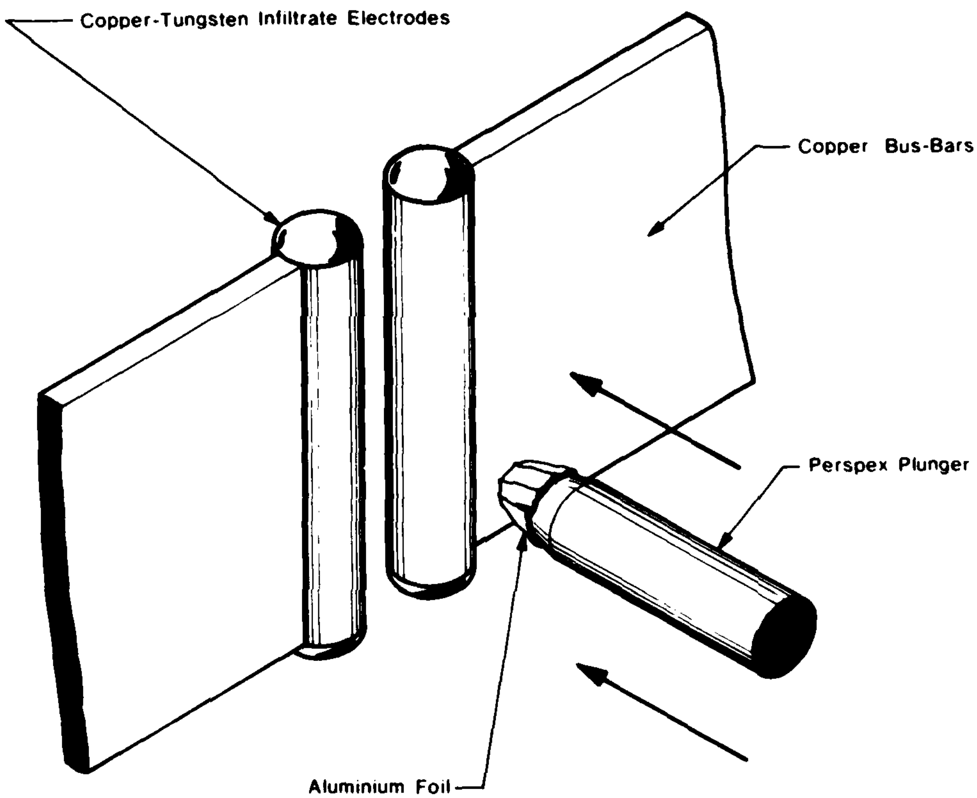
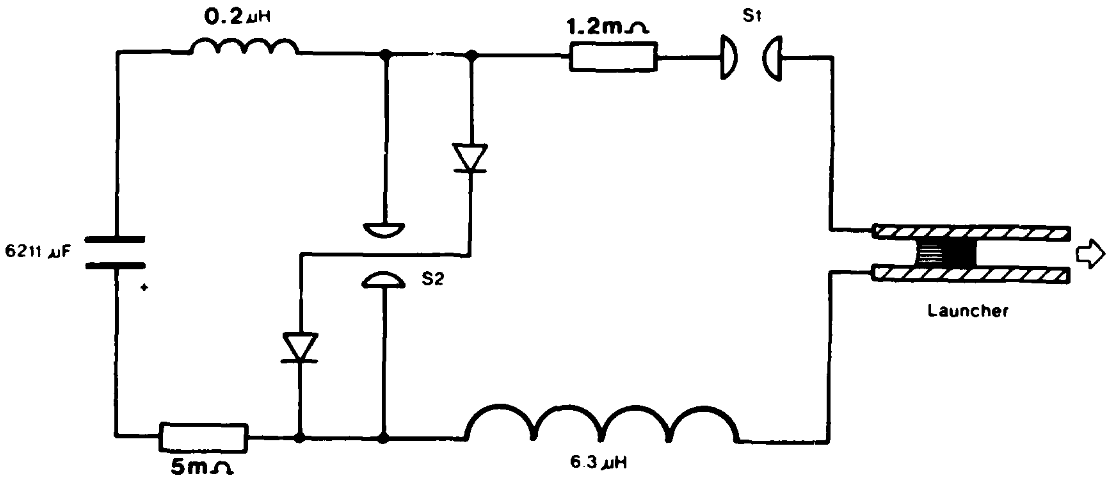


FIGURE 3 Foil initiated main spark-gap switch



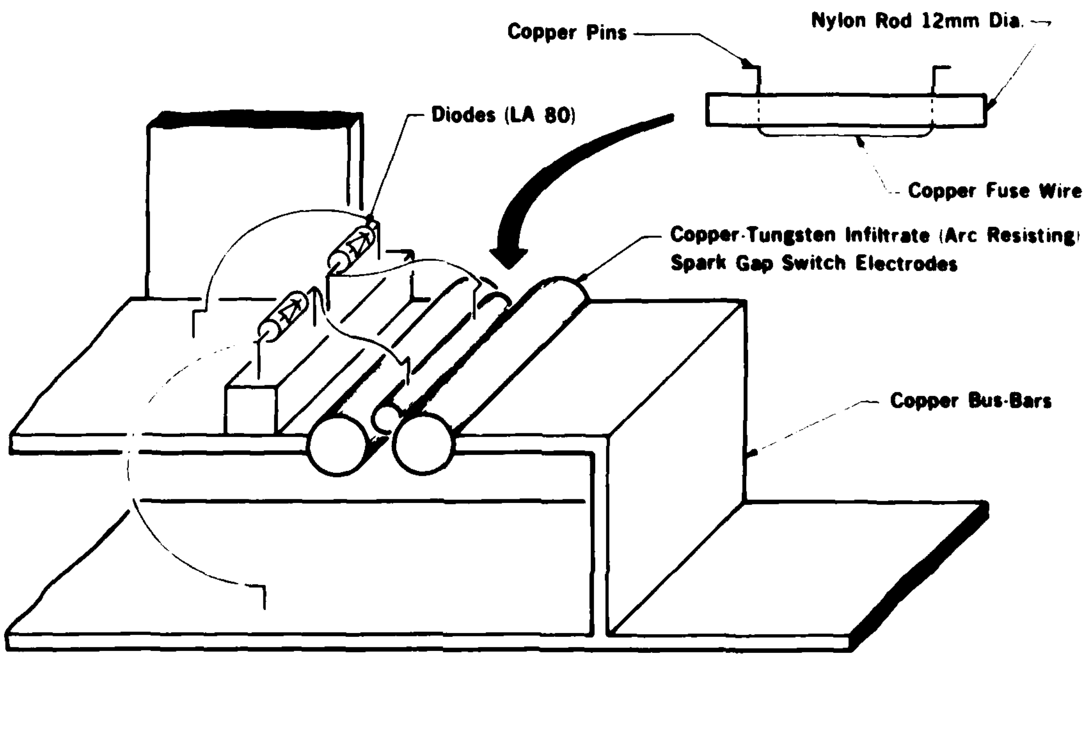


FIGURE 4 Crowbar switch circuit and basic layout used in EML firings

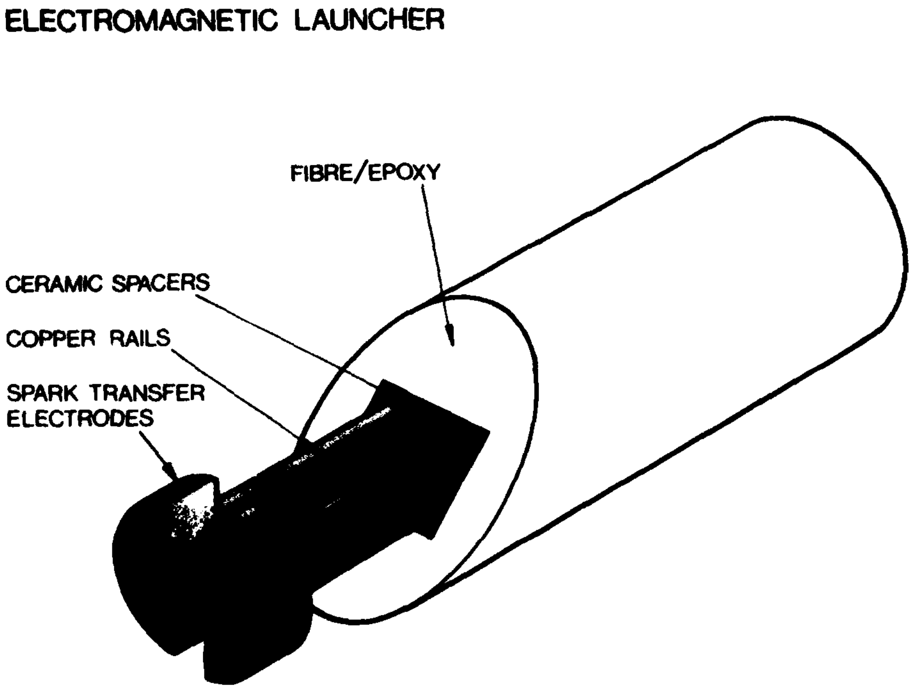


FIGURE 5 Arc discharge electrodes on muzzle end of railgun (see also figure 11b)

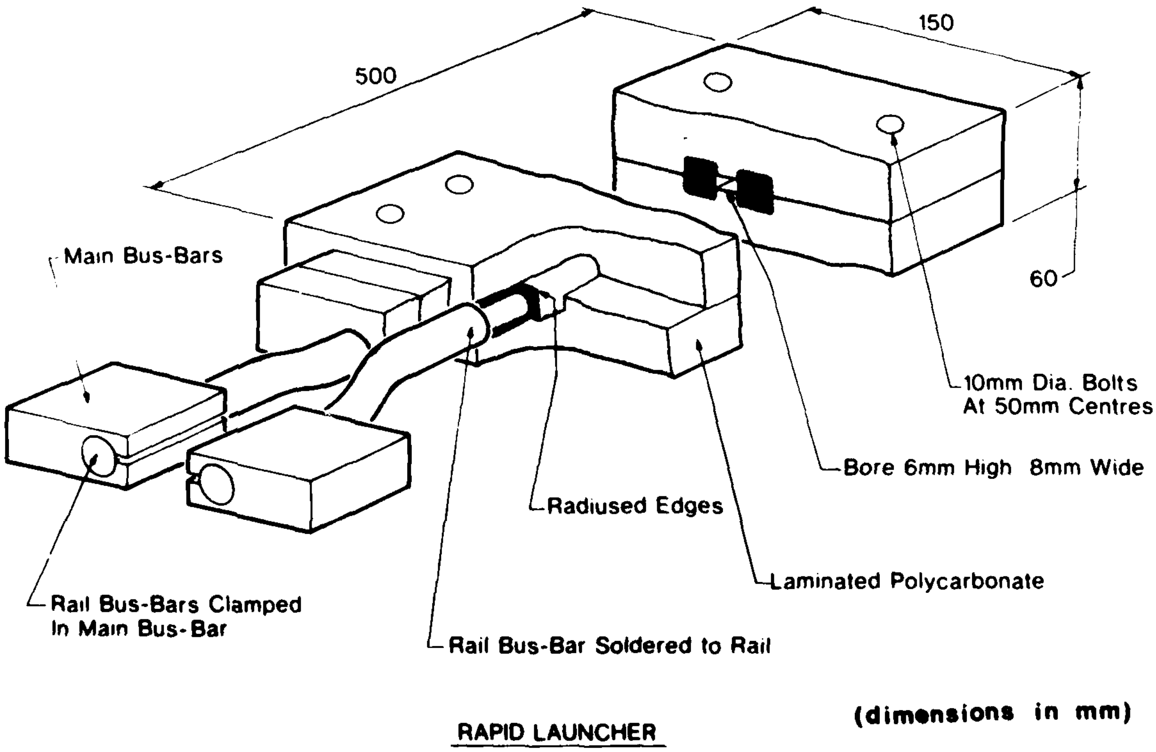


FIGURE 6 ıatic drawing showing basic features and dimensions of RAPID

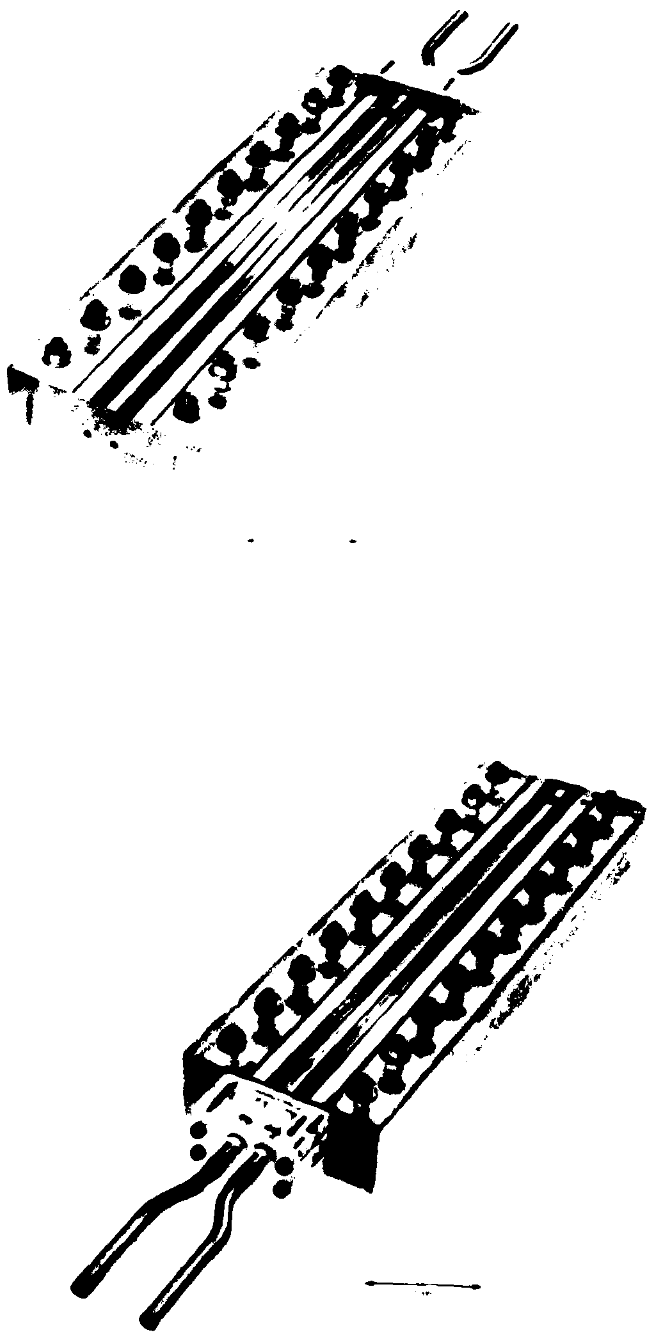


FIGURE 7 Photographs of the 500 mm long RAPID launcher. Clear polycarbonate barrel support allows photographic observations of events in the bore.

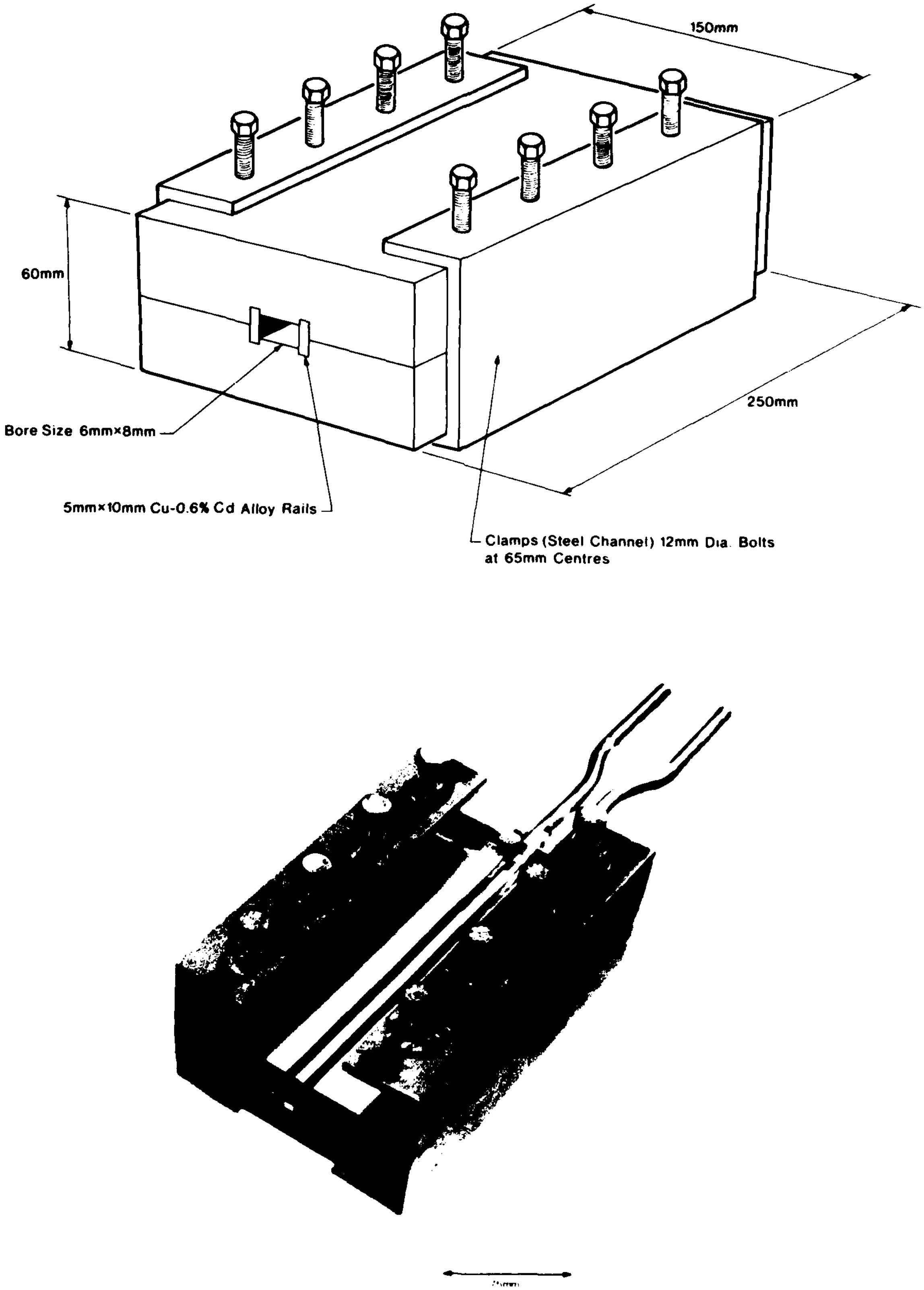
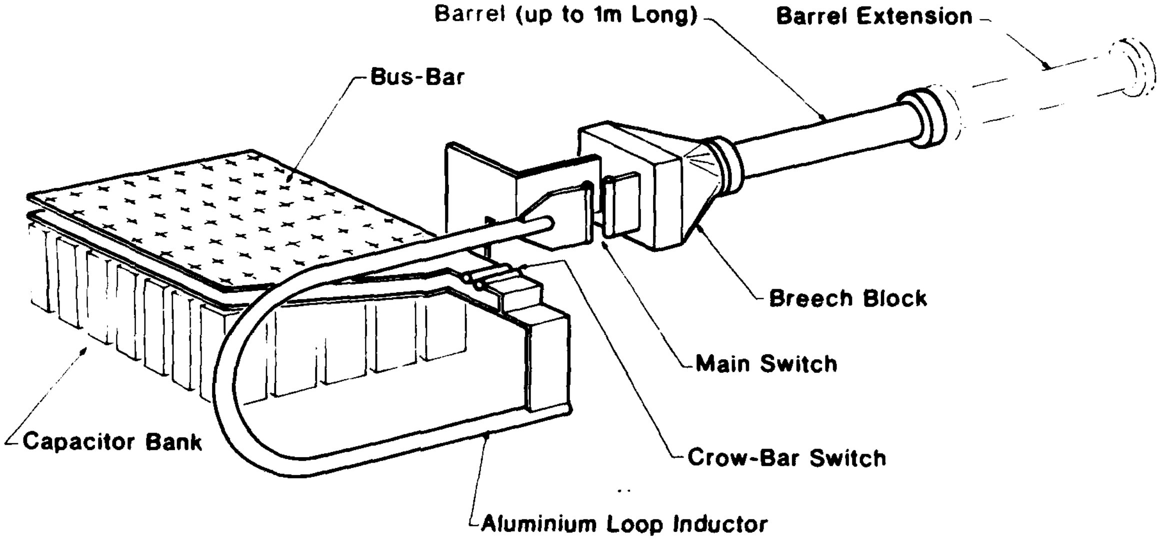


FIGURE 8   Mini-RAPID device for studying rail-damage processes
in plasma armature railguns



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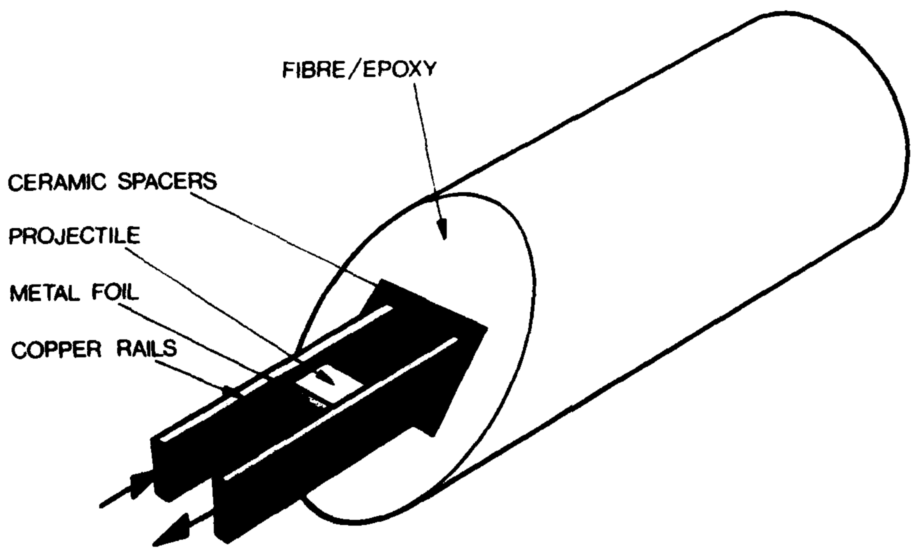


FIGURE 9 Top - layout of the ERGS railgun system

Bottom - schematic drawing showing the design features of ERGS

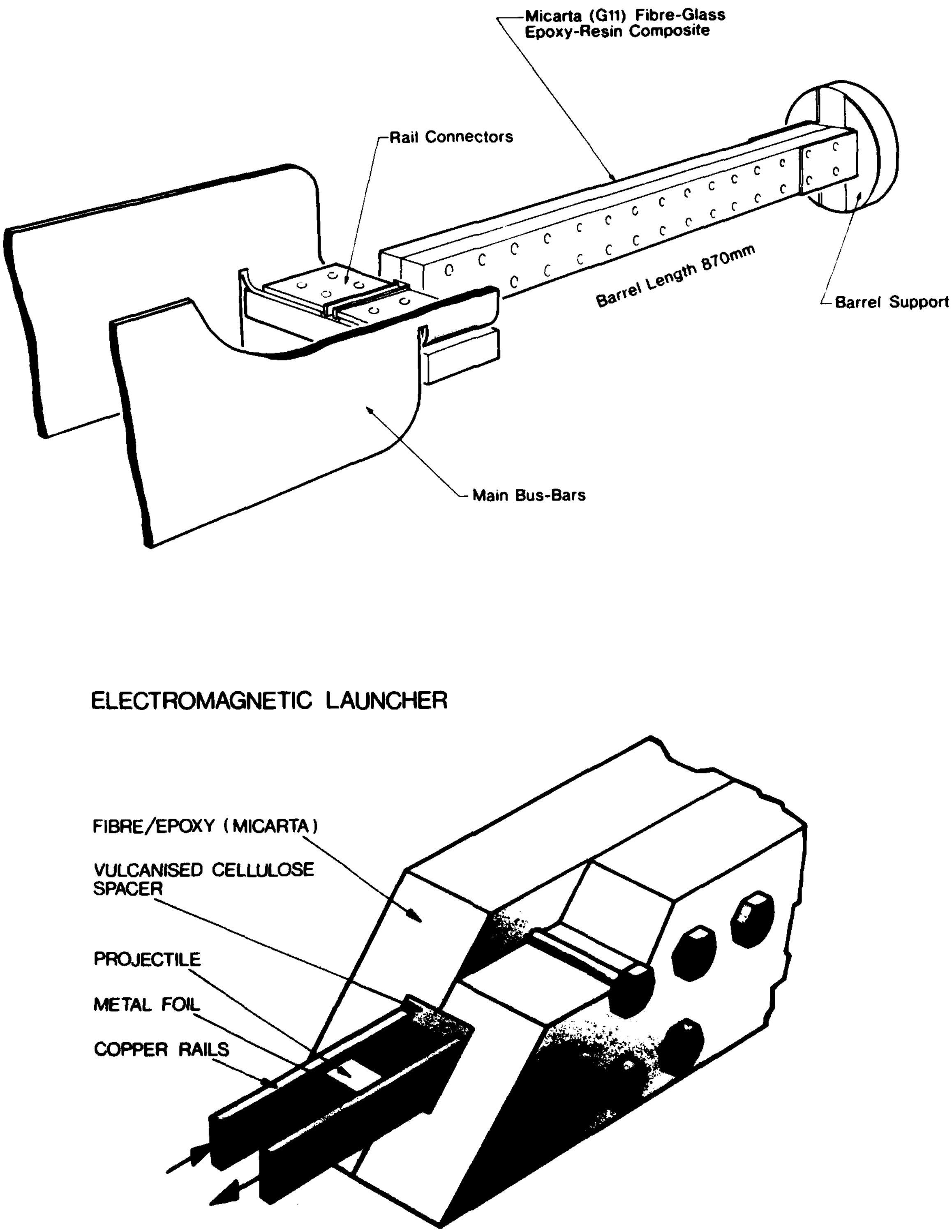


FIGURE 10 The ERGS-1M railgun; above shows basic arrangement; below is a cut-away schematic showing launcher features

ELECTROMAGNETIC LAUNCHER

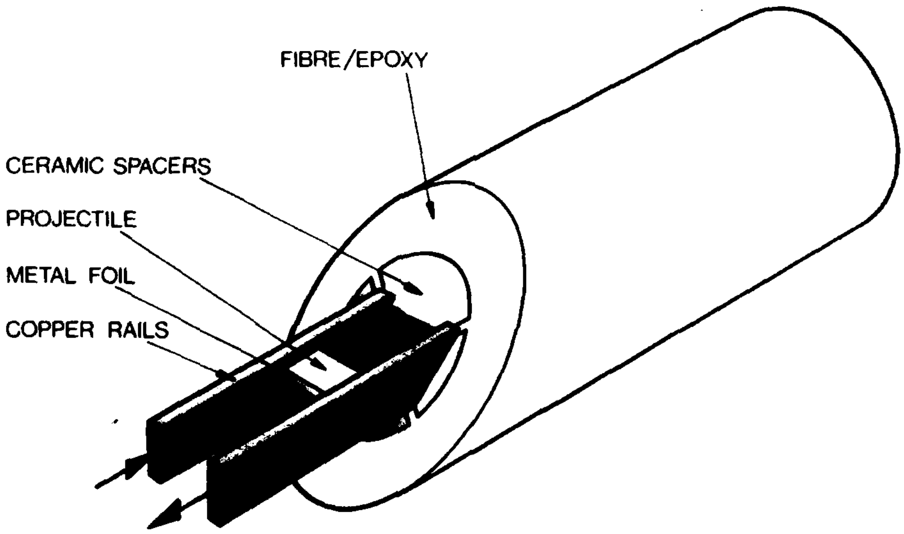


FIGURE 11a Schematic cut-away drawing of the ERGS-2 Electromagnetic Launcher

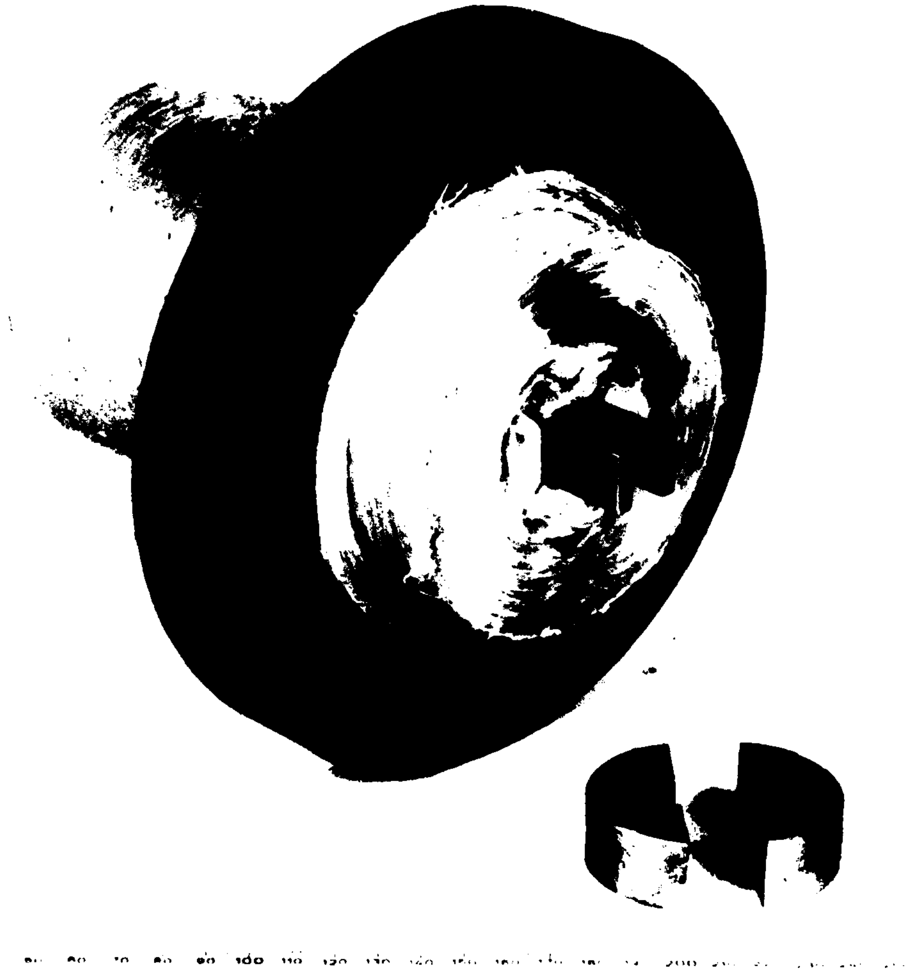


FIGURE 11b Photograph of the ERGS-2A barrel showing alumina ceramic rail supports. Outer Kevlar fibres tend to be loose after machining the outer surface to obtain nominal standard dimensions - fibre to epoxy ratio is high. Also shown are arc transfer blocks for decreasing damage to muzzle end of rails.

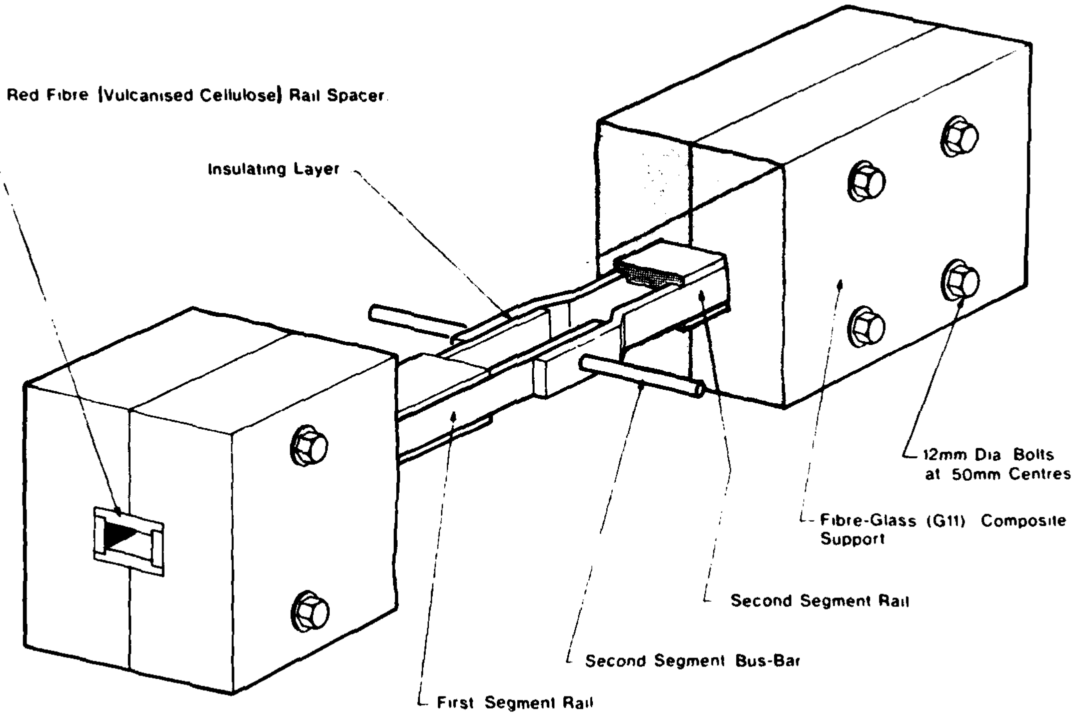
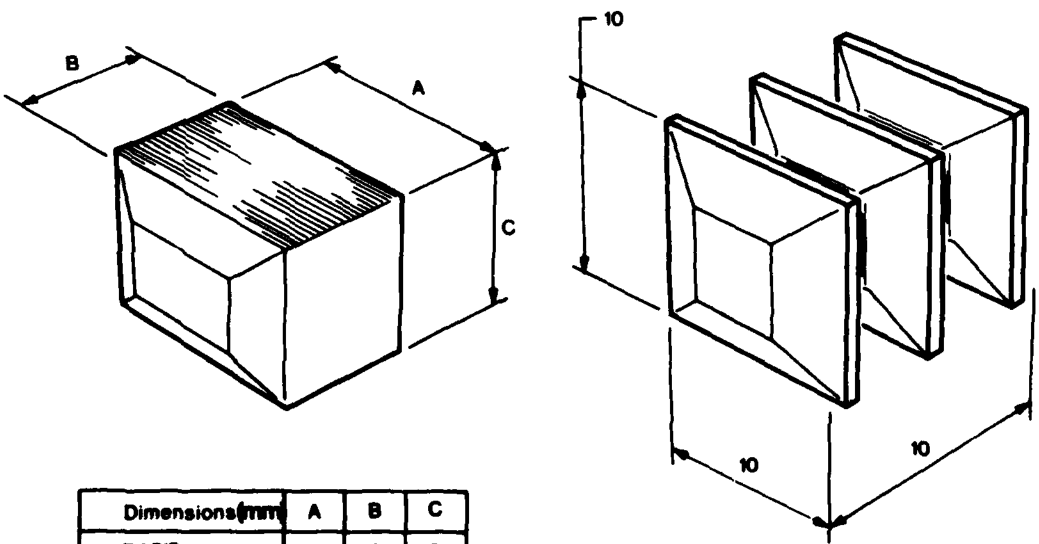


FIGURE 12 Design of segmented railgun (ERGS-3M)



Dimensions(mm)	A	B	C
RAPID	8	6	6
ERGS-1	8	8	6
ERGS-2	10	10	10

PROJECTILES

FIGURE 13 Design and dimensions of projectiles used in RAPID and ERGS railguns

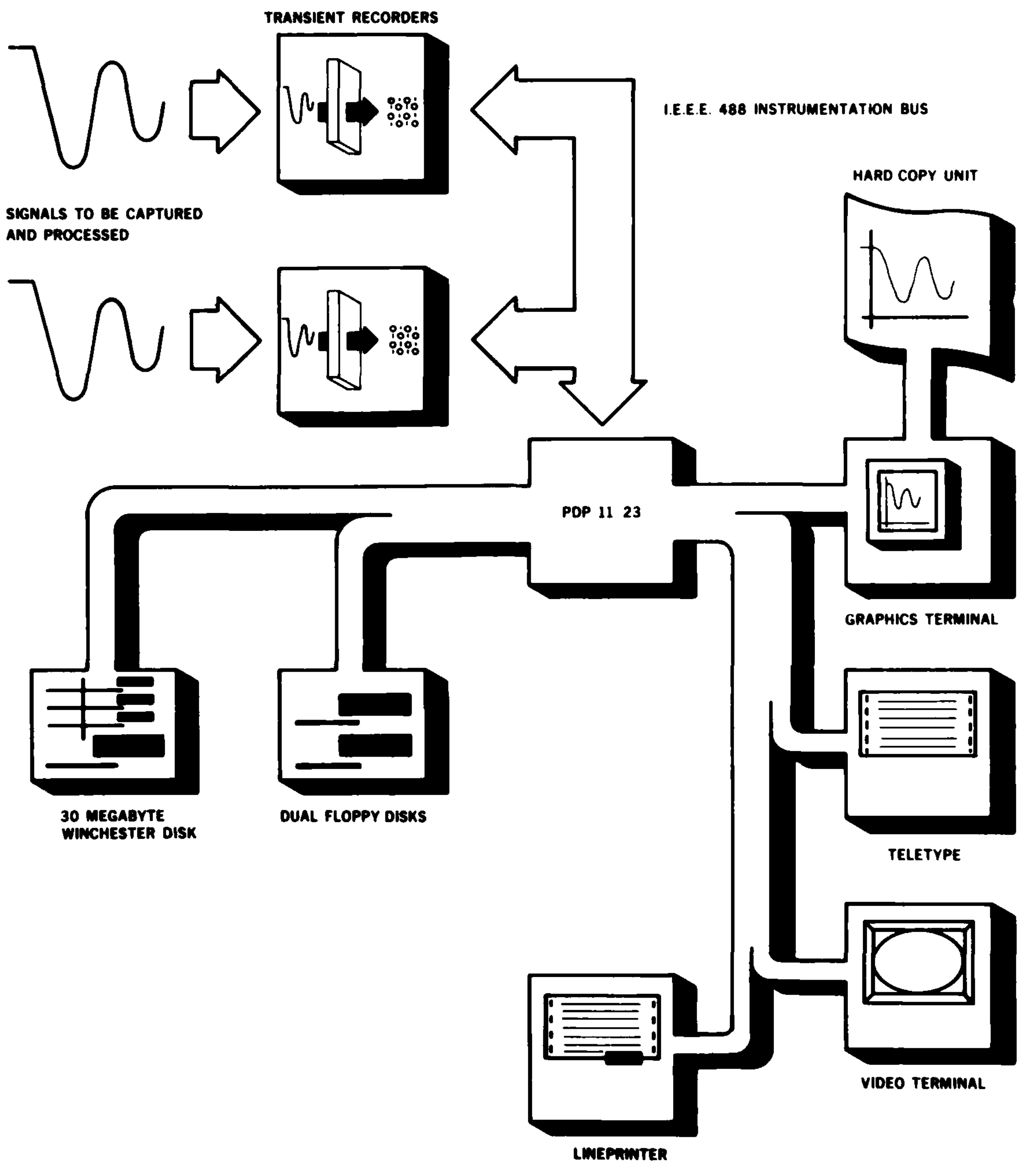


FIGURE 14 Sketch showing basic components of data acquisition and analysis system used for EML firings

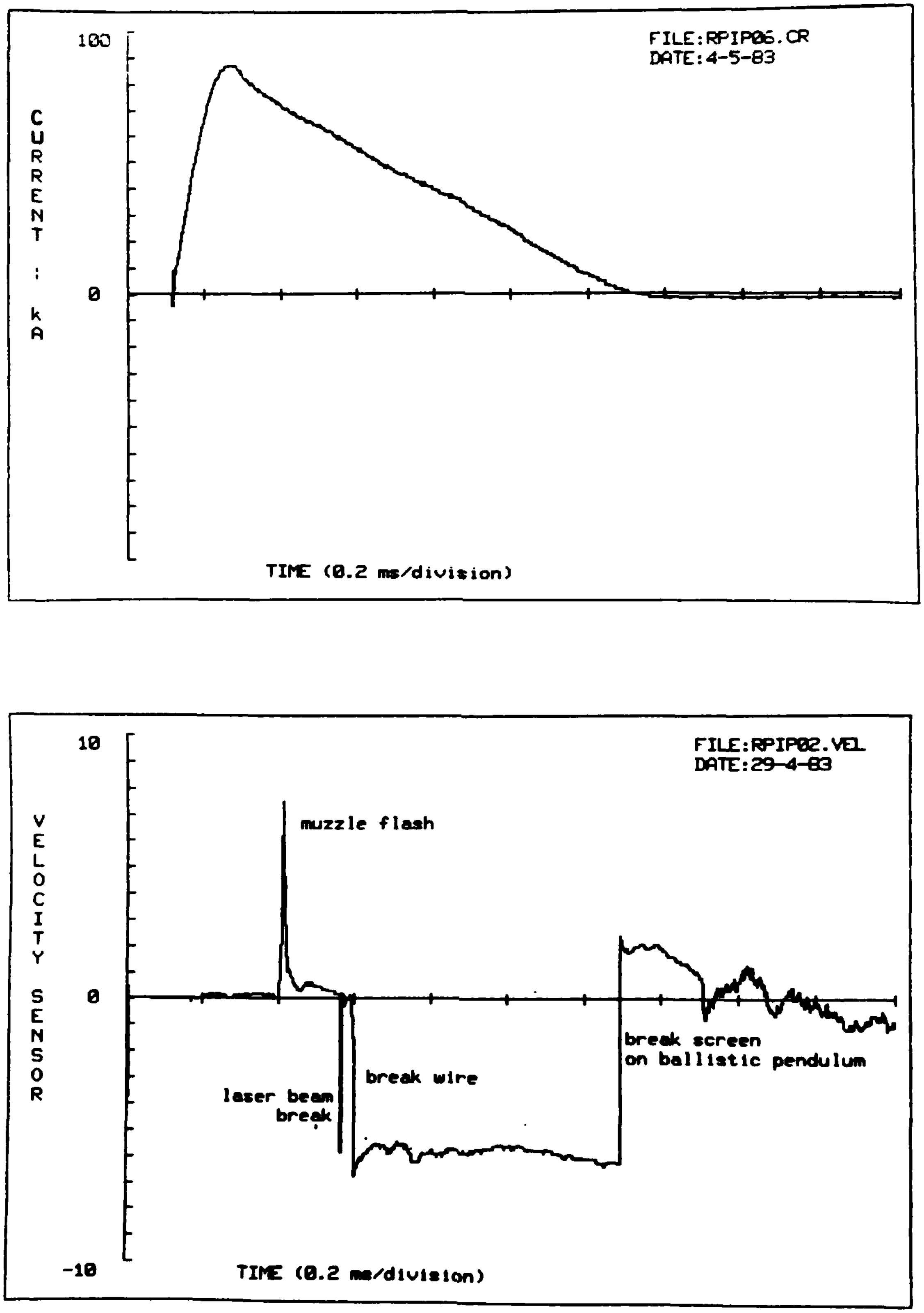


FIGURE 15 Typical recordings from a firing of the RAPID launcher

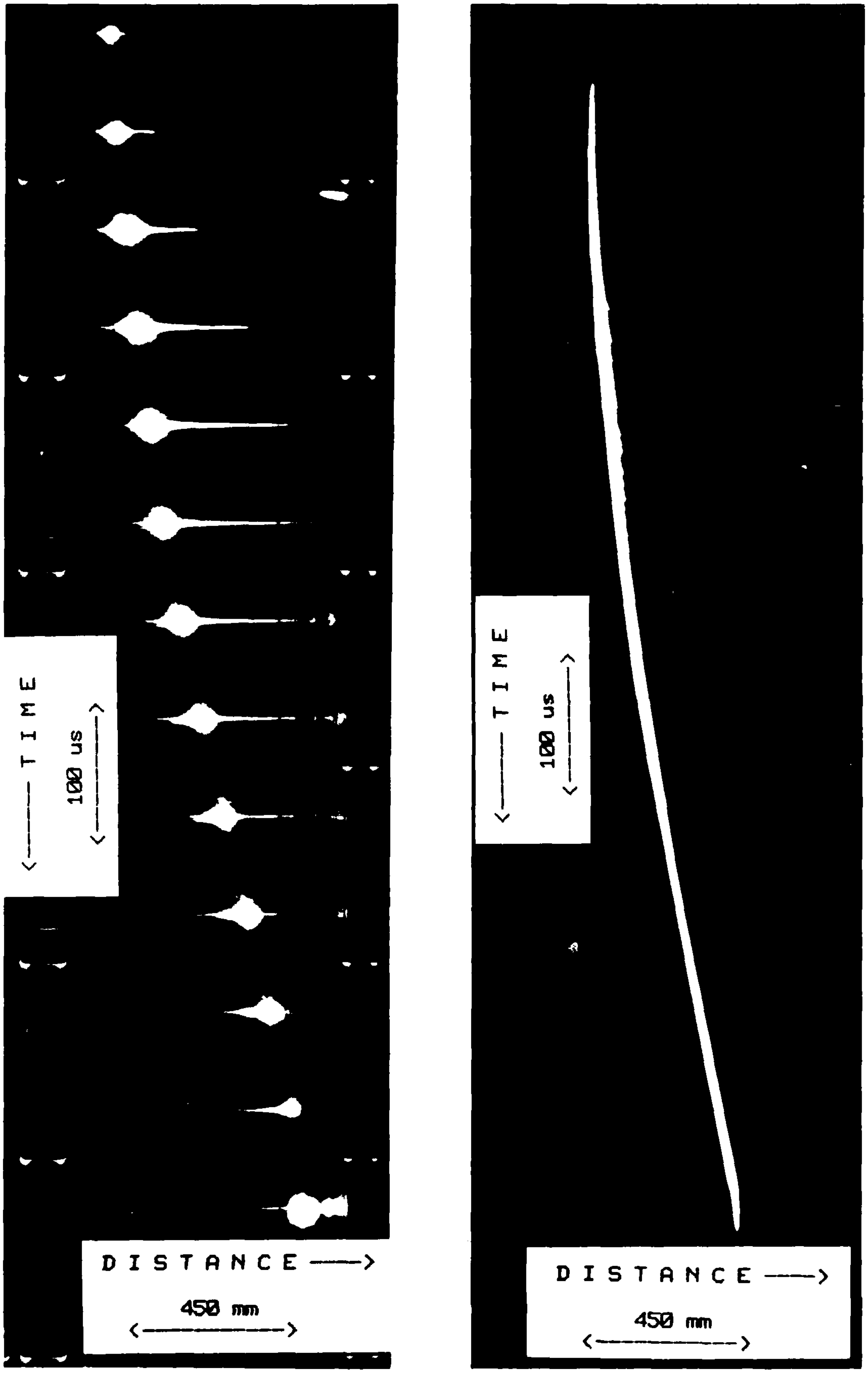


FIGURE 16 Typical framing and streak camera records from a RAPID firing

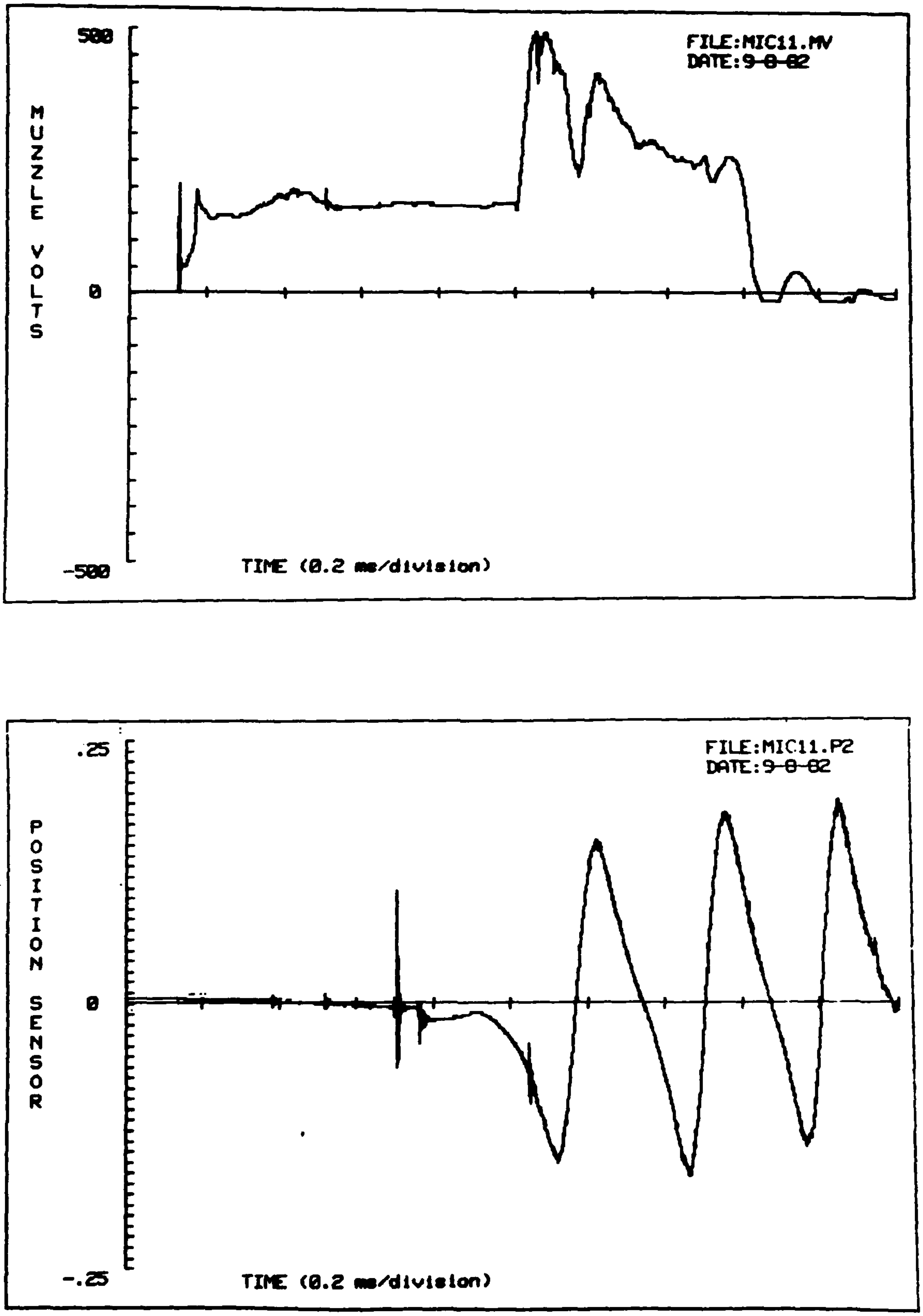


FIGURE 17   Example of results obtained in a test firing of ERGS-1M

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